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Improved and Tested: A New Generation of Cool White Dwarf Atmosphere Models

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Abstract

The photosphere of cool, helium-rich white dwarfs is notoriously tricky to model due to its fluid-like density. Using modern ab initio calculations, we have developed a new generation of atmosphere models that include an accurate description of the equation of state, chemical equilibrium and opacities under these high-density conditions. We show that our new models successfully fit objects that were poorly reproduced by previous models, notably those showing metal absorption lines.

1 Introduction

Cool helium-atmosphere white dwarfs have photospheres that are characterized by fluidlike densities ($\rho \approx 1\,\mathrm{g\,cm^{-3}}$, Bergeron et al., 1995). Under such conditions, the separation between atoms is roughly equivalent to the size of the atoms themselves and approximations usually implemented in atmosphere codes are no longer valid. In particular, the ideal gas law, the Saha ionization equation and Lorentzian line profiles must be discarded.

Recently, Kowalski & Saumon (2006) have developed a new set of cool white dwarf atmosphere models that take many nonideal high-density effects into account. Using these models they find that virtually all DC white dwarfs cooler than $T_{\rm eff} = 5000\,\mathrm{K}$ have hydrogen-rich atmospheres (Kowalski & Saumon, 2006; Kilic et al., 2009). This conclusion contradicts the results found using the models of the Montreal group (Bergeron et al., 1997, 2001; Kilic et al., 2006, 2010), according to which a significant fraction of white dwarfs cooler than $T_{\rm eff} = 5000\,\mathrm{K}$ are helium-rich. This discrepancy is problematic not only for our understanding of the spectral evolution of cool white dwarfs but also for cosmochronology. In fact, a mistake on the determination of the chemical composition of a cool DC star can translate into an error of 1 Gyr on its cooling time (Fontaine et al., 2001).

To resolve the discrepancy between both sets of models we need to test them to identify their respective shortcomings. Unfortunately, since DC stars have a featureless spectrum, they do not provide any observational way of testing the models. The spectra of DC stars are simply too easy to fit. Our solution to this problem is to use cool DZ stars, the only white dwarfs that keep showing atomic absorption lines below $T_{\rm eff} = 5000\,\mathrm{K}$. Contrarily to DC stars, cool DZ white dwarfs represent a real challenge for atmosphere models, since an accurate description of the physical conditions at their photosphere is a prerequisite to a good fit of their spectral lines. We can therefore use cool DZ stars to observationally validate our atmosphere models.

But first, in order to fit cool DZ spectra, we need to update our atmosphere code to properly capture the physics of the atmosphere of cool white dwarfs. In Section 2 we describe the additions made to our code to reach this goal. Then, in Section 3, we show how our new models perform at fitting the spectra of cool DZ stars that were poorly fitted by previous model atmosphere codes.

2 Model Improvements

This section is a brief discussion regarding the numerous improvements that had to be made to the model atmosphere code of Dufour et al. (2007) in order to accurately model nonideal effects in cool DZ stars. Additional details are given in Blouin et al. (2018), where we provide an in-depth description of our new atmosphere code.

2.1 Radiative Opacities

One of the most important improvement required to properly fit the spectra of cool DZ stars is to go beyond

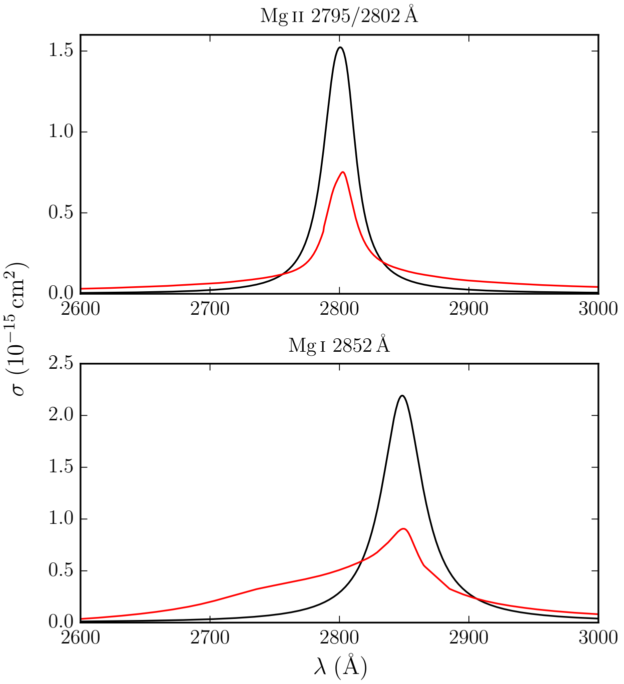

Figure 1: Absorption cross section of the Mg II 2795/2802 Å and Mg I 2852 Å lines. The black lines correspond to the Lorentzian profiles, and the red ones are the profiles obtained with the unified line shape theory of Allard et al. (1999). These profiles were computed assuming $T = 6000\,\mathrm{K}$ and $n_{\mathrm{He}} = 10^{22}\,\mathrm{cm}^{-3}$.

the usual symmetric Lorentzian line profiles and use the unified line shape theory described in Allard et al. (1999). We implemented this formalism for the strongest transitions observed in cool DZs:

- Ca I 4226 Å (N. F. Allard, private communication);
- Ca II H&K (Allard & Alekseev, 2014);
- Mg I 2852 Å (Allard et al., 2018);
- Mg II 2795/2802 Å (Allard et al., 2016b);
- the Mgb triplet (Allard et al., 2016a);
- the Na I D doublet (Allard et al., 2014).

Figure 1 shows two examples of profiles computed with the theory of Allard et al. (1999) for density and temperature conditions representative of the photosphere of cool DZ stars. Clearly, under those high-density conditions, the Lorentzian profiles completely fail to reproduce the broadening, the shift and the overall shape of the lines.

Moreover, in a dense helium medium, it is important to account for the reduction of the Rayleigh scattering and He$^-$ free-free cross sections resulting from collective interactions between atoms (Iglesias et al., 2002). We have implemented this nonideal effect using the results of Rohrmann (2018) as well as results from our own Ornstein-Zernike (OZ) calculations (see Blouin et al. 2018 for details). Finally, we also include the improved high-density H_2-He collision-induced absorption (CIA) profiles of Blouin et al. (2017) and the He-He-He CIA (Kowalski, 2014).

2.2 Equation of State

In each layer of our model atmospheres, the total number density $n_{\mathrm{tot}}(P,T)$ and the internal energy density $u(P,T)$ are computed using the ab initio equations of state (EOS) of Becker et al. (2014). As these tabulated EOS are given only for pure helium and pure hydrogen compositions, we resort to the additive volume rule for mixed compositions. At the photosphere of the coolest DZ stars, n_{tot} found using the EOS of Becker et al. (2014) can be a factor of 5 smaller than the value found when assuming the ideal gas law. This has important consequences, since most nonideal effects (e.g., metal-line profiles, chemical equilibrium) are parametrized as functions of the density. For instance, for the same pressure and temperature conditions, using the ideal gas law instead of the Becker et al. (2014) EOS would result in broader spectral lines.

2.3 Chemical Equilibrium

Under high-density conditions, atoms can undergo pressure ionization. Classically, this effect is included in model atmosphere codes using the Hummer & Mihalas (1988) occupation probability formalism. However, this approach has important drawbacks. First, the excluded volume effect assumed in this formalism is only a crude approximation of the real interaction between neutral particles. Also problematic is the fact that there is no theoretical prescription for the radii used to compute the occupation probabilities. This implies that the strength of the pressure ionization is governed by a set of free parameters.

Our implementation of pressure ionization relies on first-principles physics and hence it does not depend on any free parameter. For the ionization equilibrium of helium, we rely on the chemical model of Kowalski et al. (2007), which is based on classical fluid theory and density functional theory (DFT). In order to properly model cool DZ atmospheres, we need to extend the work of Kowalski et al. (2007) to heavy elements. Properly characterizing the pressure ionization of metals is vital for two reasons. First, we need to obtain the right ionization ratios if we want to simultaneously reproduce spectral lines of different ionization stages. Secondly, pressure ionization can have a dramatic impact on the whole atmosphere structure. In fact, metals provide most of the free electrons in DZ stars and hence they control the strength of He$^-$ free-free, which is the dominant source of opacity in the atmosphere of these stars.

The ionization equilibrium of heavy elements is assessed by replacing the ionization potential I by an *effective* ionization potential $I + \Delta I$ in the Saha equation (Kowalski et al., 2007; Zaghloul, 2009),

$$\frac{n_{K+1} n_e}{n_K} = \frac{2Q_{K+1}}{Q_K} \left(\frac{2\pi m_e k_B T}{h^2} \right)^{3/2} e^{-(I+\Delta I)/k_B T}. \quad (1)$$

Here ΔI is the ionization potential depression,

$$\Delta I = \mu_e^{\text{nid}} + \mu_{K+1}^{\text{nid}} - \mu_K^{\text{nid}}, \quad (2)$$

and μ_e^{nid} is the nonideal chemical potential of an electron, μ_{K+1}^{nid} is the nonideal chemical potential of an ion in ionization stage $K+1$ and μ_K^{nid} is the nonideal chemical potential of an ion in ionization stage K. Each of these nonideal chemical potentials can be expressed as the sum of an excess internal energy per particle and an entropic contribution. We rely on DFT to compute the first contribution and we use the OZ equation to evaluate the second one. All details regarding these calculations are given in Blouin et al. (2018). Our results show that pressure ionization of heavy elements starts at $\rho \approx 0.1\,\text{g}\,\text{cm}^{-3}$ and that the ionization potential depression reaches 1 to 3 eV at $\rho = 1\,\text{g}\,\text{cm}^{-3}$, depending on the species considered. Figure 2 gives an example of our results for Na. Interestingly, for all species considered (C, Ca, Fe, Mg and Na), our model predicts a weaker pressure ionization than the Hummer & Mihalas (1988) formalism used in conjunction with hydrogenic hard sphere radii. This result is consistent with the findings of Bergeron et al. (1991) for the ionization equilibrium of hydrogen in DA stars. They found that using radii given by $r_n = 0.5n^2 a_0$ allowed better spectroscopic fits than using the usual $r_n = n^2 a_0$ value.

3 Applications

To test the new constitutive physics implemented in our models, we turn to cool DZ stars that previous versions of our model atmosphere code were unable to fit. Here, we present a summary of our analysis of LP 658-2 (Blouin et al., 2018) and SDSS J080440.63+223948.6 (J0804+2239; Blouin et al., in preparation).

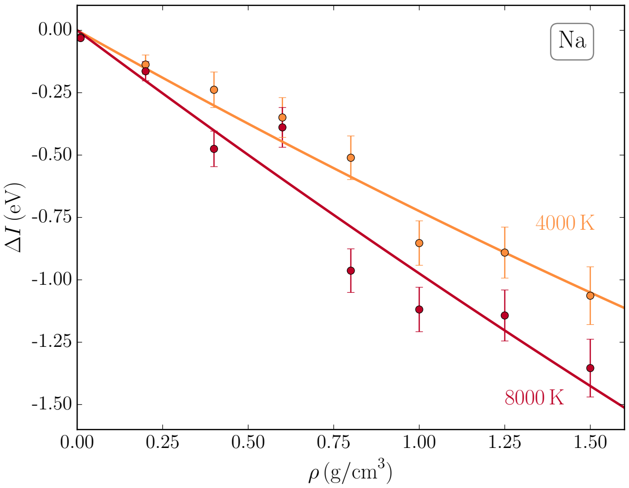

Figure 2: Depression of the ionization potential of Na surrounded by a dense helium medium. The circles show the results of our calculations (the error bars indicate the statistical error associated with the finite configuration sampling) and the solid lines are analytical fits.

3.1 LP 658-2

LP 658-2 is a cool DZ star with a weak Ca II H & K doublet. This object has been studied by many authors, but no one seems to agree on its atmospheric parameters and none has yet reached a consistent solution across all wavelengths. Bergeron et al. (2001) concluded that LP 658-2 has a helium-rich atmosphere with $T_{\text{eff}} = 5060 \pm 60\,\text{K}$, but their analysis was based on models that did not include heavy elements. Using data from the Faint Object Spectrograph (FOS), Wolff et al. (2002) concluded that LP 658-2 has a mix H/He atmosphere, since they attributed the observed UV flux deficiency to Lyα broadening. Then, Dufour et al. (2007) concluded that LP 658-2 is much cooler ($T_{\text{eff}} = 4270 \pm 70\,\text{K}$) and that it cannot contain as much hydrogen as suggested by Wolff et al. (2002), since H$_2$-He CIA would then be visible in the infrared photometry. However, the solution of Dufour et al. (2007) fails to account for the shape of the UV spectrum and their spectroscopic fit predicts a strong Ca I 4226 Å line that is not seen in the observations. Finally, Giammichele et al. (2012) suggested that LP 658-2 might be hydrogen-rich after all, since such a composition allows a better spectroscopic fit than Dufour et al. (2007), although it is incompatible with the photometry and it does not explain the UV spectrum.

Our own analysis of this object makes use of *Gaia* DR2 parallaxes (Gaia Collaboration, 2016, 2018), $BVRI$ and JHK photometry from Bergeron et al. (2001), visible spectroscopy from Giammichele et al. (2012) and UV

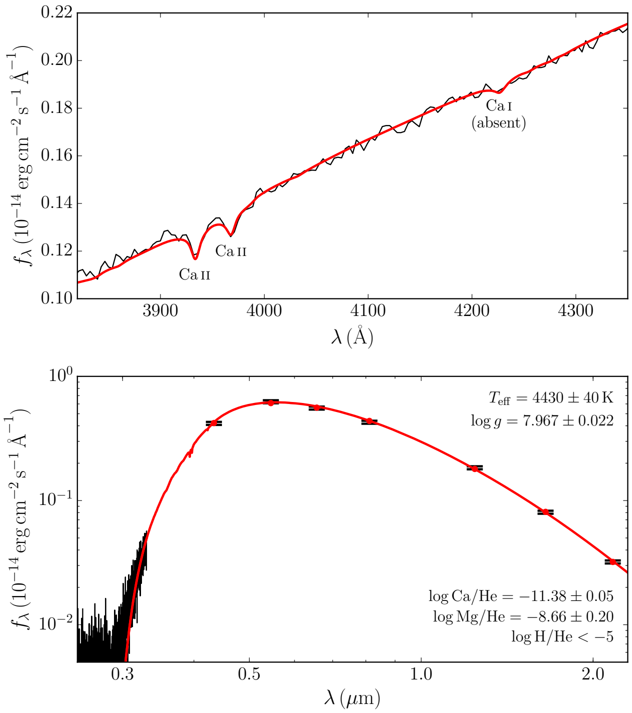

Figure 3: Our best solution for LP 658-2. The top panel shows our fit to the spectroscopic data and the bottom panel displays our fit to both the photometry and the FOS spectrum.

spectroscopy from FOS (Wolff et al., 2002). Thanks to the improved constitutive physics implemented in our code, the problems met by previous authors are now gone. We found a helium-rich solution that allows a consistent fit of the UV data, the visible spectroscopy and the photometry (Figure 3). Our new line profiles and our nonideal Ca ionization equilibrium have solved the problems that Dufour et al. (2007) and Giammichele et al. (2012) faced when trying to fit the visible spectrum. Moreover, we do not have to include hydrogen to fit the UV spectrum, since we found that the UV flux deficiency is naturally explained by trace amounts of Mg (absorption from broad Mg II 2795/2802 Å and Mg I 2852 Å spectral lines). We constrain the amount of hydrogen to H/He$<10^{-5}$, since a higher abundance would give rise to an infrared flux depletion that is incompatible with the JHK photometry.

3.2 J0804-2239

J0804+2239 was identified by Kilic et al. (2010) as the first DZ star to show CIA. The right panel of Figure 4 clearly shows the presence of CIA in this star. Pure helium models are unable to fit the infrared photometry, while mixed H/He models, where H_2-He CIA is strong, yield an excellent fit. No analysis of this star had been published up to now, because previous models were unable to simultaneously reproduce the spectral lines in the visible spectrum and the CIA observed in the JHK photometry. We had to improve both our line profiles and our CIA profiles to reach the consistent solution displayed in Figure 4. As we will show in an upcoming paper, the CIA profiles of Jørgensen et al. (2000) implemented in the prior version of our code and the Lorentzian profiles previously assumed for the Ca lines were not appropriate for the modeling of J0804+2239.

4 Conclusion

We have developed a new model atmosphere code that takes into account all nonideal effects relevant for the modeling of cool DZ stars. This includes improved line profiles and continuum opacities, a nonideal equation of state, and an accurate treatment of pressure ionization. More importantly, we have shown that our models are able to fit the spectra of cool DZ stars that previous atmosphere codes were unable to reproduce, suggesting that we properly account for the nonideal high-density effects arising in helium-rich cool white dwarfs. This result is of utmost importance in the context where observational validations of cool white dwarf atmosphere models are almost nonexistent. We can now move forward and apply our improved and tested models to a large sample of cool white dwarfs to revisit the problem of their spectral evolution.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (`https://www.cosmos.esa.int/gaia`), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, `https://www.cosmos.esa.int/web/gaia/dpac/consortium`). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This work used observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA).

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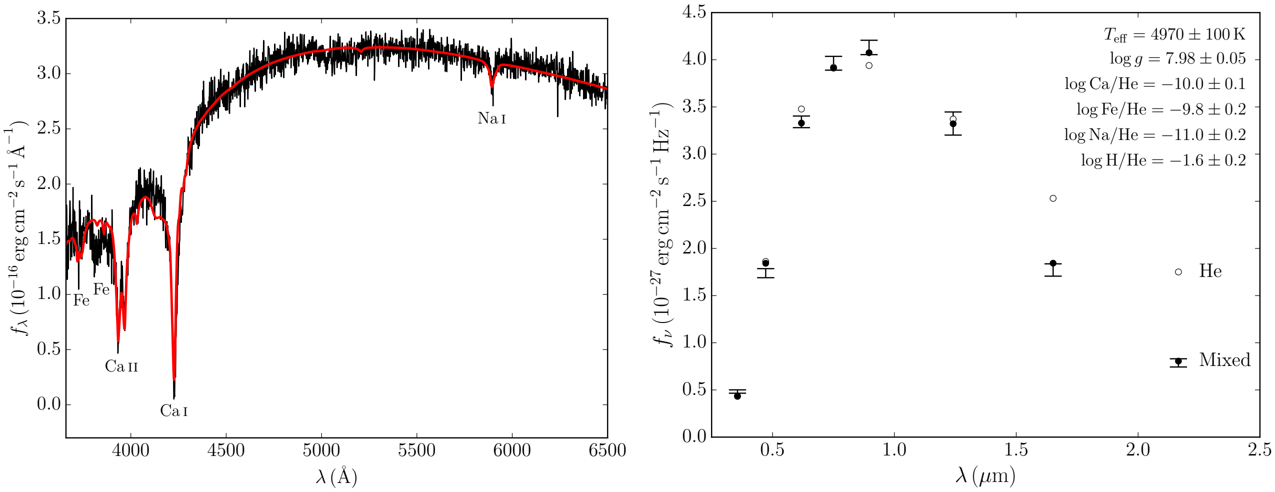

Figure 4: Our best solution for J0804+2239. The left panel shows our fit to the spectroscopy and the right panel displays our fit to the photometry. The filled circles in the right panel represent our best solution (for which the atmospheric parameters are given in the top right corner) and the open circles show our best fit if we assume a hydrogen-free atmosphere.

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